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Solar micro-energy harvesting based on thermoelectric and latent heat effects. Part II: Experimental analysis

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ABSTRACT

This study investigates, experimentally, the use of thermoelectric generators with phase change materials (PCM) to harvest micro-renewable energy. Experimental results in the laboratory and in real loading conditions show that the coupled effects of heat flux (solar radiation), external temperature and convection (wind) significantly influence the micro-energy harvest. Unlike other approaches, the proposed system is able to produce micro-energy by day and by night, thanks to the release of solar heat stored in the PCM during the day. With optimized thermal loading, power generation of 0.8 mW was achieved by one work unit. The experimental results also show the sensitivity of the proposed work unit to variations in solar radiation and wind, and this indicates that the system (consisting of many work units) would be suitable for use as a sensor and actuator in wireless applications in buildings.

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1. Introduction

One of the scientific problems in micro-energy harvesting encountered over the last 10 years concerns autonomous energy systems and sensor–actuator systems powered by ambient renewable energy. The objective is to reduce the maintenance costs of battery-powered devices and to operate autonomous devices in adverse environments. Potentially useful forms of ambient energy are thermal, light, mechanical energy etc. Using these sources, several devices, from the centimeter scale down to the micro-scale, have been developed. Many researchers, especially those working on micro-systems (micro-electro mechanical systems, or MEMS) are concentrating on developing devices for micro-energy harvesting. They have applied many different techniques [1–11] based on multiphysics coupling effects in materials. There are various methods for powering portable devices:

(i) Semiconductor devices: Polarized solar cells are used to convert photovoltaic-solar energy directly into electrical energy. According to Cook-Chennault et al. [1], the power generated is in the range of 80–3000 W/cm^3 of active material, with a voltage in the range of 0.05–5 V.
(ii) Piezoelectric devices (mechanical vibrations): Several devices, from the millimeter scale down to the micro-scale, have been developed, with average powers in the 10 μW–10 mW range (0.01–100 W/cm^3 for 0.05–15 V) [1,2,3,6].
(iii) Electrostatic method: The relative movement between electrically insulated charged capacitor plates produces electrostatic energy which is harvested [7].
(iv) Electromagnetic method: The electromagnetic induction arising from the relative motion (rotation or linear) between a magnetic flux and a conductor is used [8]. The harvested power is similar to that of piezoelectric devices.
(v) Thermal methods: Thermal energy (temperature gradient) is converted into electrical energy using, for example, the Seebeck effect [9]; alternatively, time temperature variation is converted through the pyroelectric effect. Innovative solutions are now proposed commercially. Some of the applications may be found in the Enocean® product description. For thermal energy, the harvested power [1] is in the range of 5–500 W/cm^3, with generated voltages of between 0.5 and 10 V.

For a given material and technique, the output power and operating conditions greatly depend on the available energy source and its effect as effective loading (light level, vibration amplitude and frequency, external temperature gradient and duration).

This article focuses on the experimental aspect of a new concept analyzed numerically in our previous research [12]. The principle of the proposed concept is based on the thermoelectric effect coupled with latent heat. The work unit as described in Part I [12] uses the heat storage capacity of the PCM to change an ambient time varia-

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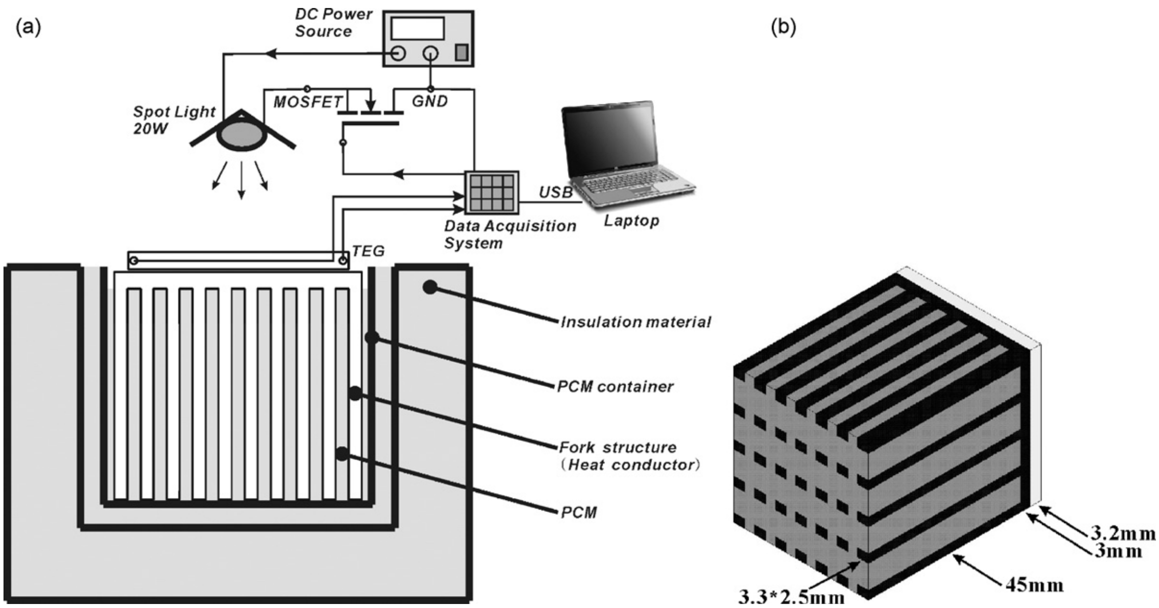

Fig. 1. (a) Diagram of experimental setup and (b) Spatial model of work unit.

tion of thermal loading into a space variation of temperature on a thermoelectric generator (TEG). The PCM was placed at the back of the TEG where it is not irradiated by sunlight. A fork-shaped structure was used to improve the internal thermal conductivity of the PCM. Such a work unit is expected to harvest energy by day and by night.

In many previous experimental studies on TEGs, a high temperature gradient is applied without considering how this high temperature gradient can be generated. In ambient thermal load as variable solar radiation, the challenge is to find a way of realizing temperature gradient on TEG as high as possible while taking into account convection effects.

In this experimental study, we experimentally show (i) the PCM operating to improve temperature stability on one face of the TEG and (ii) the TEG with PCM gives better performance than the TEG without PCM. In Section 2, we describe the materials and experimental methods. In Section 3, we present and discuss the experimental results.

2. Experimental method

An experimental system as shown in Fig. 1a was set up to investigate the performance of the thermoelectric generator. The experimental system was composed of: (i) the work unit and (ii) the solar radiation simulator.

2.1. Setting up the work unit

In our single work unit, there are five basic components:

- A thermoelectric module: A commercially available thermoelectric module, TEC-12708, measuring 40 mm × 40 mm × 3.2 mm. Its equivalent Seebeck coefficient is 30 mV $^{\circ}C^{-1}$ and its internal resistance is 2.5 Ω. These parameters are obtained in advance by method introduced in literature [13].
- A fork structure: An optimized geometry of the fork is illustrated in Fig. 1b. There are 35 fingers in total, each measuring 3.3 mm × 2.5 mm × 45 mm. The connecting part of the fork is 3 mm thick and it is thermally connected to the TEG by heat-conductive silicon grease.
- Phase change material: A hydrated salt was chosen as the PCM in the experiment. Fig. 2a shows the latent heat properties of the PCM against temperature. It indicates that the melting point of the hydrated salt is around 28 °C and that its maximum latent heat available is 3.2×10^8 Jm^{-3}.

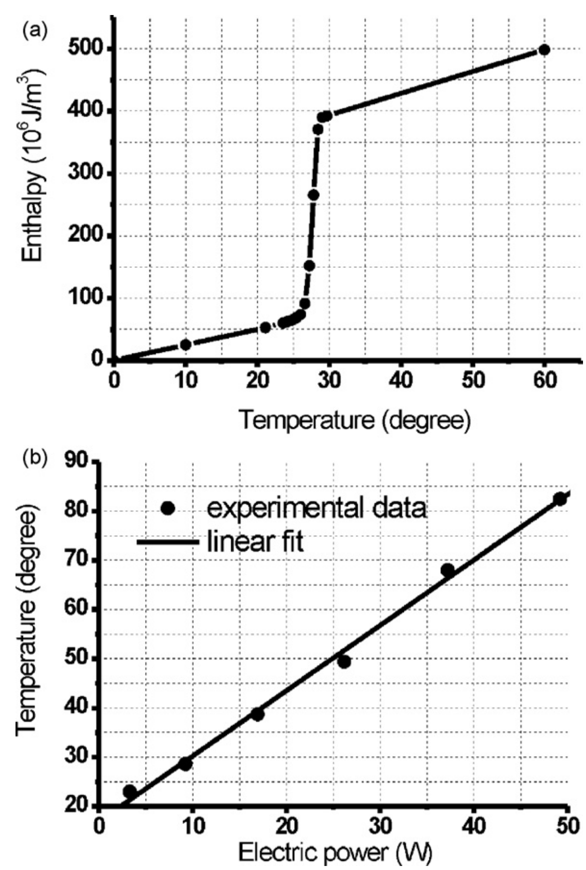

Fig. 2. (a) Enthalpy of PCM as a function of temperature and (b) transformation between input electrical power for spotlight and input heat for TEG.

Table 1
Material properties of elements of the work unit.

	TEG (TEC-12708) solid	Fork structure (aluminum) solid	PCM (hydrated salt) liquid/solid	Heat insulation (polystyrene) solid
K (W m^{-1} °C^{-1})	0.5	210	0.54/1.1	0.04
C (J °C^{-1} kg^{-1})	800	900	2165/1546	1300
ρ (kg m^{-3})	3900	2700	1710/1530	30
L (×10^{-3} m)	40	40	40 ± 2	200 ± 5
W (×10^{-3} m)	40	40	40 ± 2	200 ± 5
H (×10^{-3} m)	3.2	48	50 ± 1	160 ± 5

- A PCM container: The liquid PCM material was put in a container and the fork structure was placed in PCM.
- Insulation material: In order to retain the heat stored in the PCM, polystyrene insulating material was shaped to enclose the PCM container as shown in Fig. 1a. To complete the PCM insulation, the air gap between the PCM container and the insulating material was filled with polystyrene foam.

The main material properties of these components are detailed in Table 1.

In order to compare the performance of the proposed work unit with another TEG system, we made a basic system which connected a piece of thermoelectric module (TEC-12708) to a large heat sink (63730, AAVID THERMALLOY) through heat-conductive silicon grease.

2.2. Approximate laboratory model of solar radiation

To illustrate the feasibility of the proposed concept over a fixed period and also in laboratory conditions (independent of the high variability in actual solar loading), we developed a system which simulated solar radiation with an electric spotlight and wind with a mini-fan.

We used an automatically controlled 20 W (12 V) spotlight in the laboratory; it provided the TEG with a maximum radiation intensity of approximately 1250 W m^{-2}, assuming that 10% of the electric power is transformed into input heat. A data acquisition system (NI USB-6259 BNC) was used to generate arbitrary signals. A direct current (DC) power source and a MOSFET IRF740 form the driving circuit for the spotlight. The data acquisition system recorded the generated voltage from the TEG at the same time as it generated the control signal for the spotlight.

Real solar radiation is a complicated physical process that we approximated in two steps:

First we determined the best distance between the spotlight and the TEG for maintaining a linear transformation of the electric power to the equivalent heat flux. After several calibration tests, the distance was set at 2 mm. Fig. 2b shows a typical curve of temperature as a function of electrical power. The distance between the temperature sensor head and the spotlight is 2 mm. As the sensor head is a linear device, the heat input is proportional to the resultant temperature. The curve shows a linear transformation of the electric power to heat flux.

Then we used a MOSFET switch to adjust the intensity of radiation and applied a linear control strategy (Pulse Width Modulation, PWM) to manage the device. The input power is proportional to the duty cycle of the square-wave control signal. The transformation from the duty cycle to the equivalent heat flux on the TEG was linear. As described in [14], a duty cycle which varies as a gauss function can generate the solar radiation required. When the solar simulator was in operation, the frequency of the control signal was 50 Hz and the refresh rate was 1 MHz. The value of the gauss function was normalized at between 0 and 1250 W m^{-2}. The intensity of the simulated solar radiation was adjusted manually with the voltage regulator on the DC power source.

The fan was placed on the side of the TEG as shown in Fig. 1a. The input power of 1.32 W provided a wind speed of 2.5 m s^{-1} on the surface of the TEG; it was computer controlled and driven by MOSFET.

3. Experimental results and discussion

3.1. Temperature stability on one face of the TEG due to PCM

When the TEG is in operation, one important effect of the PCM is the improvement in temperature stability on the contact face, as predicted in our theoretical study [12]. The stability was investigated by the experiment described below.

A mini temperature sensor head (K-type thermocouple) was placed on the edge of the contact face, between the TEG and the fork structure and a constant 1250 W m^{-2} heat flux was applied to the hot face of the TEG. The temperature variation was recorded for two cases:

(i) The fork was placed on a desk in the laboratory.
(ii) The fork was inserted in the PCM.

Temperature increase is shown in Fig. 3. As the initial temperature for these two tests was different, the temperature was normalized to a relative value based on the initial temperature of each test. The temperature of the fork without PCM increased linearly over time while that of the fork with PCM tends towards a constant value. After 0.15 h one can see that the relative temperature variation of the fork with PCM is smaller than that of the fork without PCM. After 0.3 h of heating, the temperature of the fork without PCM is higher than that of the fork with PCM. These results show that the PCM improves temperature stability on the contact face between the TEG and the fork. This stability could be further increased by improving the design and fabrication of the fork structure as well as by choosing PCM with better latent heat characteristics.

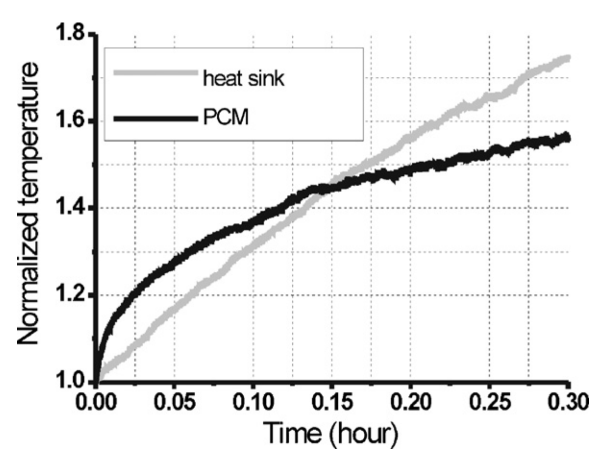

Fig. 3. Temperature variation on cold face of the TEG with PCM and without PCM.

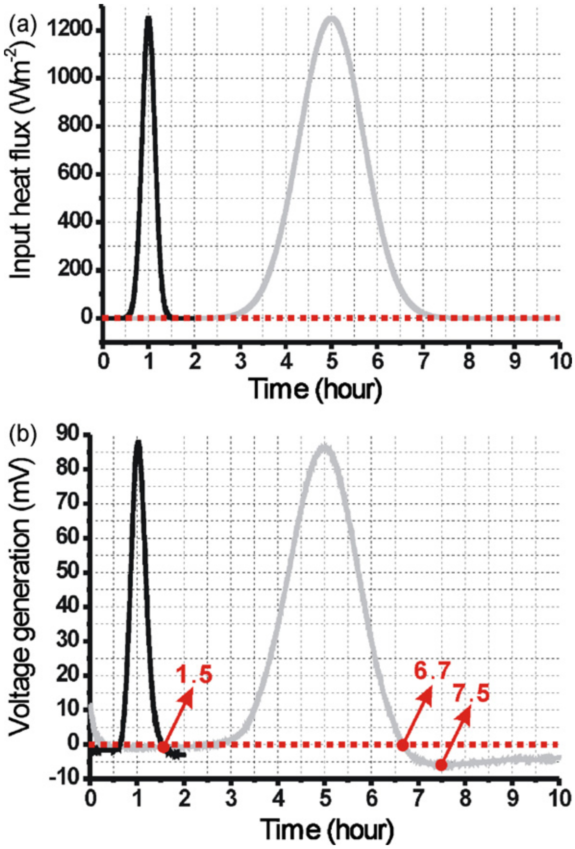

Fig. 4. (a) Typical representative solar radiation in the laboratory and (b) voltage generation with representative solar radiation.

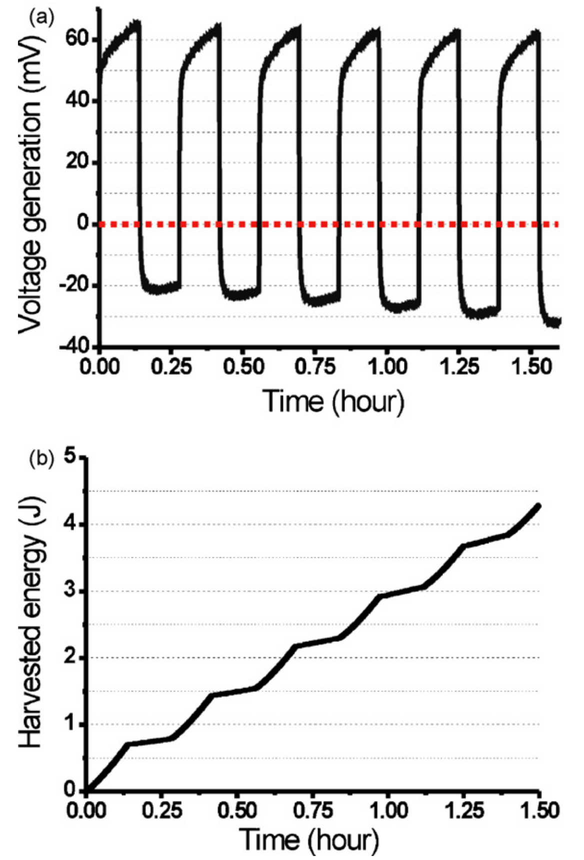

Fig. 5. (a) Continuous voltage generation with alternate radiation and forced convection and (b) continuous energy harvested with alternate radiation and forced convection.

3.2. Energy harvesting with simulated solar radiation in the laboratory

Fig. 4a shows two representative curves of the daily solar radiation used to analyze the proposed concept in the laboratory. The first curve is for a period of 2 h and the second is for 10 h.

At the start, considered as midnight, radiation was off. When the intensity of radiation reached its maximum value ("midday"), the heat from the spotlight to the TEG was 1250 W m^{-2}. The gauss function used to generate the intensity of heat flux $H_f(t)$ is:

$$H_f(t) = 1250 \times e^{\frac{-(t-0.5T)^2}{2(0.07T)^2}} \tag{1}$$

where T is the representative work period (2 and 10 in our experiment).

An optimized external resistor of 2.5 Ω was connected to the TEG to measure power generation. In the experiment, the distance between the spotlight and the TEG was fixed at 2 mm and the voltage was regulated at 12 V. At the start, the PCM was completely solid, and the room temperature was close to 20 °C. The corresponding voltage generation over the two work periods is shown in Fig. 4b. It should be noted that:

(i) The PCM operated as a heat source after storing energy during the day and the generated voltage changed from a positive to a negative value after the radiation decreased to a relatively low value. The turning point was at 1.5 h for the 2 h work period, when radiation is already zero. This was not the case for the 10 h work period, as the turning point was at 6.7 h, when the radiation still maintained a certain low value; the radiation was zero at 7.5 h in this case. These three important times are indicated in Fig. 4b. The difference between the two cases implies that there is a suitable work period for a given volume of PCM. The later points of view are all based on the experiment with a work period of 2 h.

(ii) The voltage generation associated with input heat is linear while the radiation increases. This makes it possible to estimate energy harvesting with a complicated heat input.

(iii) The generated negative voltage (for the 2 h work period) is very low compared to the positive voltage (30 times lower at peak value). This suggests that the temperature gradient on the TEG is too low at night. This may be due to insufficient natural convection on the top face of the TEG. The slow movement of air in the laboratory and the proximity of the spotlight to the TEG limit both horizontal and vertical convection.

(iv) The total energy harvested in 2 h with the optimized external resistor is 3 J, corresponding to an average power of 400 μW.

In order to study the influence of convection and to determine the maximum performance in the laboratory of the proposed work unit, a fan was used to provide convection which was further increased by moving the spotlight further from the surface of the TEG: from 2 mm to 7 mm.

In this experiment, constant radiation and forced convection were applied as the thermal loads on the TEG. The two loads were applied alternately: when the radiation was on, the fan was off, and vice versa.

The intensity of the radiation was less than 1250 W m^{-2} and the forced convection, described as wind speed, was 2.5 m s^{-1}. A duty cycle of 1000 s was chosen for the energy-harvesting process. The generated voltage and the harvested energy are shown in Fig. 5.

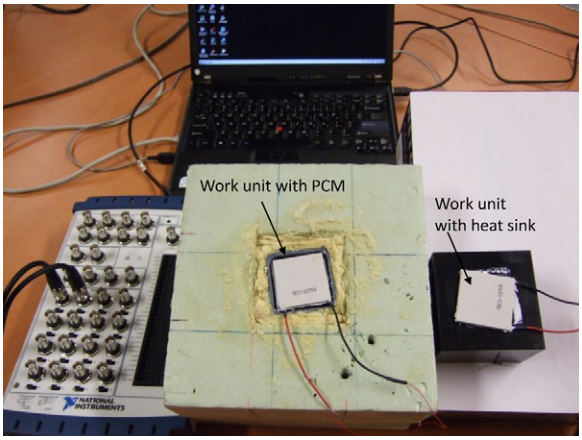

Fig. 6. Typical energy-harvesting system: work unit with PCM and work unit with heat sink.

The average power generation in this experiment was 800 μW, which was also the maximum mean value in the laboratory. The contribution from PCM as a heat source was 20% in each cycle, demonstrating that convection is a favorable condition for energy harvesting at night. It should be noted that the mean value of voltage generation continued to decrease, indicating that the convection was still not strong enough. Extra thermal loading such as low ambient temperature could improve the performance.

The working efficiency of the energy-harvesting process in the laboratory depends on the intensity of radiation, but it is also influenced by convection. Methods of significantly altering the convection effect could be used to improve system performance in a real situation. One of these methods is to cover the upper face of the work unit with a glass.

3.3. Energy harvesting in a real situation

The work unit with PCM was compared to the unit without it. Both were loaded by solar radiation in real conditions. The experimental setup is shown in Fig. 6.

The experiment was conducted from 11:16 on the 1st of November to 08:06 on the 2nd of November in Aix-les-Bains, France. There was sunshine for the first 3 h, and the glass was used to cover the upper face of the PCM work unit to reduce the convective effect of the wind at that time. When the solar radiation ceased, the glass was taken off. Since the PCM acts as the heat source, increased convection improves the performance of the system.

The unit without PCM was exposed to external conditions during the whole test. The optimized 2.5 Ω external resistor was connected to both of the energy-harvesting systems: the voltages generated are shown in Fig. 7a. Analysis of this figure led to four comments:

(i) Convection is an important factor in the performance of TEG. The PCM work unit with reduced forced convection presented better voltage generation than the TEG with normal forced convection when solar radiation is the heat source. Stronger forced convection takes more heat energy from the hot face of the TEG during the day and decreases the temperature on this face. It ultimately reduces the voltage generation.

(ii) The strong forced convection and the low ambient temperature are both favorable when the PCM is the heat source. The peak value of generated negative voltage was half that of the positive voltage. It increased 15 times more than in the energy-harvesting process in the laboratory. The peak value of generated positive voltage is 30 times that of negative voltage, as shown by representative solar tests in the laboratory.

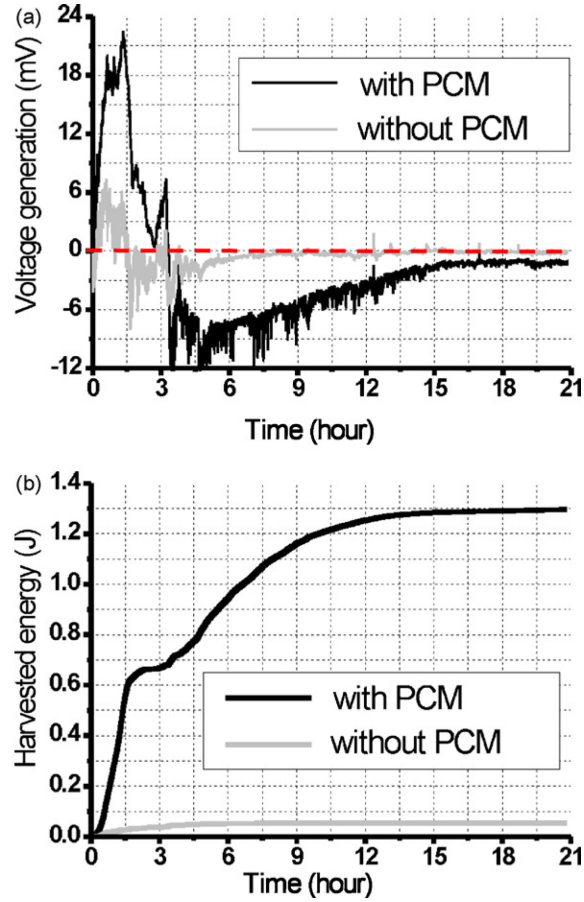

Fig. 7. Comparison of (a) voltage generation and (b) harvested energy in actual solar radiation between work units with and without PCM.

(iii) The energy-harvesting period of the PCM work unit is four times longer than that of the unit without PCM. The harvested energy is 1.3 J over 21 h, which represents an average power of 17 μW, as shown in Fig. 7b. Energy harvested at night by the PCM work unit forms half of the total energy. The absolute power generation in this real situation (in autumn) is small compared to the maximum value achieved in the laboratory. However, it indicates that the performance of our system is heavily dependent on the three types of actual thermal loading (solar radiation, forced convection associated with wind speed and daily temperature variation).

(iv) Voltage generation was very sensitive to both solar radiation and wind speed (Fig. 7a). The significant reduction in positive voltage which started at hour 1.5 was due to cloud reducing the radiation, and the tiny vibration of negative voltages was due to variations in wind speed. Variations in voltage generation can be used by smart control strategies in some processes.

A previous experiment over one year showed that the laboratory loading conditions which resulted in our system's good performance (wind about 2.5 m s^{-1}, solar radiation about 1200 W m^{-2} and outside temperature about 20–30 °C) are closer to summer loading conditions than to winter conditions, as shown in Fig. 8. So it seemed possible that the experimental values of 0.8 mW could be obtained on a summer, or at least a sunny day.

There are many ways of improving the efficiency of the proposed work unit, some of which would involve the improved efficiency of the TEG and the use of more suitable PCM, more efficient insulation

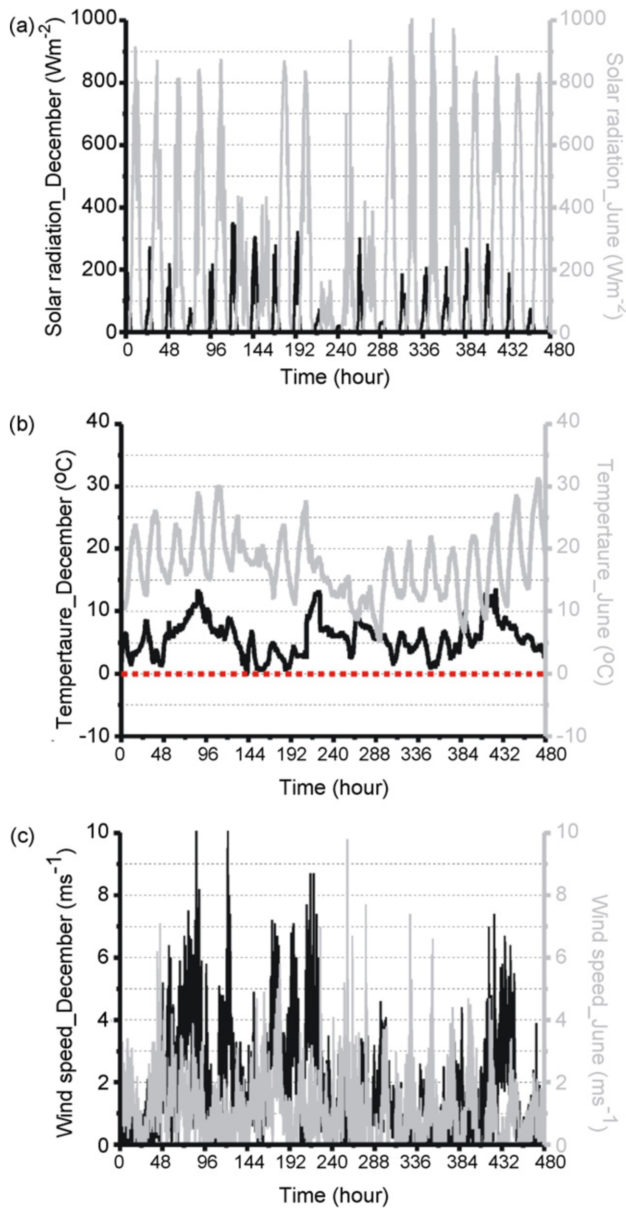

Fig. 8. Typical loading of work unit during December and June (a) intensity of solar radiation, (b) temperature in environment and (c) wind speed.

and black paint on the sunny face of the TEG in order to increase the absorption of solar radiation. Such improvements would enhance the power generation based on the thermoelectric module with phase change material.

4. Conclusion

A hybrid method of harvesting solar micro-energy has been experimentally considered. The device uses the energy storage capability of Phase Change Material (PCM) to maintain a relatively stable temperature on one side of the TEG and to extend the useful working period. We have shown, by experiment, that the work unit with a fork structure embedded in PCM performs well.

The influence of convection and heat flux on energy harvesting has been shown, both in the laboratory and in real conditions. We have shown experimentally, in real loading conditions, that it is possible to harvest solar micro-energy with the proposed work unit by day and by night. The interaction between the latent heat effect, convection and solar radiation is important to our work unit's energy harvesting. We also showed that power generation with optimized thermal loading in the laboratory reaches 0.8 mW for one work unit. These results shed light on a promising new method of harvesting micro-energy. The proposed work unit has great sensitivity to variations in solar radiation and wind which, coupled to its power-generation capacity, make it suitable for use as sensor and actuator for energy saving in buildings.

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